NASA Technical Memorandum 101624

AVSCOM Technical Memorandum 89-B-005

REDUCTION OF BLADE-VORTEX INTERACTION NOISE USING HIGHER HARMONIC PITCH CONTROL

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(NASA-TM-101624) REDUCTION OF BLADE-VORTEX INTERACTION NOISE USING HIGHER HARMONIC PITCH CONTROL (NASA. Langley Research Center) 20 p CSCL 20A

N89-27465

Unclas

G3/71 0223909

JULY 1989

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

US ARMY
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REDUCTION OF BLADE-VORTEX INTERACTION NOISE USING HIGHER HARMONIC PITCH CONTROL

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ABSTRACT

An acoustics test using an aeroelastically scaled rotor was conducted to examine the effectiveness of higher harmonic blade pitch control for the reduction of impulsive blade-vortex interaction (BVI) noise. A four-bladed, 110 in. diameter, articulated rotor model was tested in a heavy gas (Freon-12) medium in Langley's Transonic Dynamics Tunnel. Noise and vibration measurements were made for a range of matched flight conditions, where prescribed (open-loop) higher harmonic pitch was superimposed on the normal (baseline) collective and cyclic trim pitch. For the inflow-microphone noise measurements, advantage was taken of the reverberance in the hard walled tunnel by using a sound power determination approach. In the paper, initial findings from on-line data processing for three of the test microphones are reported for a 4/rev (4P) collective pitch control for a range of input amplitudes and phases. By comparing these results to corresponding baseline (no control) conditions, significant noise reductions (4-5 dB) were found for low-speed descent conditions, where helicopter BVI noise is most intense. For other rotor flight conditions, the overall noise was found to increase. All cases show increased vibration levels.

SYMBOLS

a_0	speed of sound in test medium, ft/sec
C_T	rotor thrust coefficient, thrust/$\rho\pi R^2(\Omega R)^2$
M_T	hover tip Mach number, $\Omega R/a_0$
nP	n'th harmonic of rotor rotational period
R	rotor radius, ft
α	rotor tip path plane angle referenced to tunnel streamwise axis, deg
α'	effective α corrected for closed-wall wind tunnel effect, deg
Γ	tip vortex strength, ft^2/sec
Θ	calculated "full-scale helicopter" flight descent angle, positive in descent, deg
θ	pitch angle of blade at Ψ, deg
θ_C	amplitude of higher harmonic pitch at Ψ_C, deg
μ	advance ratio, tunnel flow velocity/ΩR
ρ	density of test medium, slug/ft^3
Ψ	blade azimuth angle, deg
Ψ_C	blade azimuth angle selected for θ_C, see Fig. 3, deg
Ω	rotor rotation frequency, rad/sec

INTRODUCTION

Impulsive blade-vortex interaction (BVI) noise, due to blade interaction with shed vortices of preceding blades, has been a major topic of rotorcraft acoustics research for a number of years. One noise reduction concept[1] is that decreases in blade lift and/or vortex strength at the blade-vortex encounters should reduce the intensity of the interactions and thus noise. An application of this idea is illustrated in Fig. 1 showing the rotor blades undergoing higher harmonic pitch angle variations. It is quite apparent that pitch control would not only modify pitch but would also modify the strengths of the shed vortices as well as possibly the interaction locations. The amplitude and phasing of such pitch controls may be expected to be important to the noise problem, since the strongest BVI occurrences tend to be located within a limited rotor azimuth angle range of the first rotor quadrant[2] (roughly between $\Psi = 45°$ and 75°). It appears therefore that although, historically, higher harmonic control of pitch

has been studied as a means to reduce helicopter vibration levels (for example see reference 3), its use to reduce noise offers potential.

This paper reports the initial finding of a rotor test designed to evaluate the noise reduction benefit of higher harmonic pitch control. The test approach involves the measurement of noise and vibration with and without prescribed higher harmonic pitch inputs superimposed on the normal cyclic trim pitch. Uniquely, the acoustic testing was conducted in a heavy gas (Freon-12) flow medium, rather than air, and the reverberant field of the hard wall tunnel test section was used to advantage by making acoustic measurements using a sound power determination approach.

EXPERIMENT

The test was conducted using the Aeroelastic Rotor Experimental System (ARES) in the Langley Transonic Dynamics Tunnel (TDT). The test setup, with in-flow microphones mounted upstream and downstream of the rotor model in the test section, is shown in Fig. 2. The tunnel test section is 16 ft. square with cropped corners. In the TDT, either air or Freon-12 gas can be used as the test medium. The advantages of using Freon-12 for aeroelastic testing of scale model rotors are discussed in reference 4. For this test , Freon-12 at a nominal density ρ of .0046 slug/ft^3 (nominal tunnel pressure of .45 atmosphere) was used. The 110 in. diameter dynamically-scaled rotor has untwisted NACA 0012 section blades with a 4.24 in. chord. The articulated flap and lead-lag hinges are offset 3 in. from the center of rotation.

Because this was the first aeroacoustic test to be conducted in a heavy gas medium, detail flow-noise calibrations were performed in the TDT for both air and Freon-12. The results reinforced the conclusions of a scaling law analysis, using fundamental aeroacoustic equations, that acoustic pressures are readily scaled between test media. To address microphone sensitivity questions for the Freon-12 medium, a special calibration was performed prior to the tunnel test. It was found that

for a medium pressure of 950 psf (corresponding to tunnel test conditions), the microphones had almost the same diaphragm sensitivity (within 0.2 dB) as air at one atmospheric pressure. As for microphone body diffraction effects on sensitivity, the acoustic wavelengths for identical frequencies in Freon-12 are smaller by the ratio of the speed of sound for Freon-12 and air, $(a_0)_{freon}/(a_0)_{air} = 500/1130 = .43$. However, for matched Mach number conditions, the test speeds (rotor and tunnel) are reduced by the same ratio thereby reducing frequency and rendering the same wavelengths for the same rotor harmonics for both air and Freon-12. Therefore the microphone response at specific harmonics of the blade passage frequency is the same in Freon-12 as if the test on this model had been conducted in air. With the noise data interpretation being straight forward, a net test advantage is found for using a heavy gas medium for this aeroacoustic rotor test because the rotor is dynamically scaled and the Reynolds numbers are higher (by 17 percent for this test) compared to air.

Twelve one-quarter inch diameter B&K pressure type microphones, six upstream and six downstream of the rotor model, were used to make the noise measurements. Figure 2 shows the microphones fitted with nose cones and mounted in vibration isolated streamlined microphone stands. Because of the reverberant character of the TDT test section, it was decided not to attempt directivity measurements but to employ the microphone distribution shown and special noise field calibrations to determine sound power spectra. Figure 2 shows that the microphones are placed away from the nearfield of the rotor BVI noise source region. The present report includes data from the indicated microphones at 16 and 13 feet upstream and a microphone at 13 feet downstream from the rotor model center . The normally open slots in the tunnel wall were covered to further enhance test section reverberance, thereby reducing statistical variance of noise measured between microphones.

Blade pitch motion is input to the rotor by moving the swashplate with three hydraulic actuators. For this four-bladed rotor, the higher harmonic pitch is achieved by superimposing 4/rev (4P) swashplate motion upon basic fixed swashplate collective and cyclic (1P) flight control inputs. Four/rev collective pitch motion (all 4 blades pitching the same way simultaneously), as well as pitch schedules containing 3P, 4P, and 5P pitch harmonic components, are possible by phasing the 4P inputs[3,5]. For this test, a specially developed computer-based open-loop control system was used to superimpose the higher harmonic pitch signals on the ARES control system. The pitch motion achieved, as well as the test procedure, can be described with the aid of Fig. 3 which shows blade pitch angle data versus blade azimuth angle for a specific flight condition. For a given advance ratio and tip path plane angle, the mean collective (6.5°, for the case shown) required to achieve the prescribed C_T and the basic 1P (3.8°) pitch control for zero flapping trim, with respect to the rotor shaft, were attained. Once aeroelastic and acoustic data were taken for this baseline case, prescribed higher harmonic pitch was superimposed to obtain a deflection of θ_c at azimuth angle Ψ_c and data again taken. For some rotor conditions, small adjustments were necessary in the mean collective and cyclic to maintain identical C_T and trim flight conditions, although none were needed for the case of Fig. 3. The 4P higher harmonic pitch portion (obtained by subtraction of the total from the baseline case) is seen at the bottom of the figure. The net pitch is seen not to be purely a 4P collective, but contains other harmonics due to normally occurring pitch-flap and pitch-lag couplings. For the 4P collective noise data shown in this report, the higher harmonic collective pitch amplitude θ_c at azimuthal angle Ψ_c in the first quadrant ($0 \leq \Psi_c < 90°$) is defined in the manner shown in Fig. 3.

The rotor was tested over a broad range of operating conditions where the rotor thrust coefficient C_T was maintained at 0.005. Rotor advance ratios μ less than 0.11

were not possible due to wind tunnel minimum operating speed limitations. The rotor rotational speed was $\Omega = 650$ rpm (the hover tip Mach number was nominally $M_T = 0.62$). Specific test flight conditions were defined based on the tunnel referenced tip path plane angle α and the advance ratio μ at the specified C_T. For the data presented, the tip path angles were corrected[6] to account for the closed wall wind tunnel effects to obtain equivalent freestream α' values. Also, in order to interpret the noise results in terms of full scale flight conditions, equivalent flyover descent angles Θ were calculated[7] based on fuselage-rotor drag of a MBB BO-105. A portion of the test was concerned with a specific pitch control containing 3P, 4P, and 5P components, but this paper only deals with results for the 4P collective pitch control.

RESULTS AND DISCUSSION

The noise data presented were obtained on-line during the test from the three microphones mentioned earlier. The microphone signals were analog band-pass-filtered between 200 to 1600 Hz (3 dB down at 4.5 and 37 blade passage harmonics) to emphasize the impulsive BVI dominated portion of the noise. The sound pressure levels for each microphone were averaged to obtain a single dB value for each test point. Although little meaning is attached to the absolute dB values for present purposes, the relative levels and trends should follow that of more detailed analyses. A detailed sound power analysis, using all 12 microphones for all the data, has not been completed.

In the results to follow, the levels include contributions from not only impulsive BVI noise, of particular concern here, but also from other harmonic and broadband noise sources.[7] Harmonic noise from unsteady, but non-impulsive, loading can be expected to be significant for operating conditions where BVI noise is diminished. This would be especially true with the increased blade motion unsteadiness associated with the pitch controls tested. Also, broadband noise from blade-turbulent

wake interactions (BWI) will contribute. For climb conditions, broadband self noise from blade boundary layer sources will be important.

Noise level results are presented in Fig. 4 for ten different flight conditions, where the rotor operated at baseline (without higher harmonic pitch) and also where 4P pitch was used at different amplitudes and phases. Fig. 4(a)-(c) are for steep descent angles where the rotor wakes are primarily above the plane of the rotor. Part (a) is for a advance ratio of $\mu = 0.17$ and helicopter descent angle of $\Theta = 9.1°$ (respective tip path plane angles α and α' are shown in parentheses). The noise levels are plotted versus the input azimuthal angle Ψ_C corresponding to the amplitude θ_C. The amplitudes tested of $\theta_C = -0.5°$ and $-1.0°$ are indicated by the symbols. The baseline case ($\theta_C = 0°$) is shown positioned at the $\Psi_C = 0°$ plot location, for convenience. The noise results represented by solid symbols are repeat test points to be subsequently discussed. It is seen, for the Fig. 4(a) flight case, that the noise level increases above the baseline condition for all 4P cases shown, especially near $\Psi_C = 0°$ and 60°. The larger control pitch of $\theta_C = -1.0°$ produced the larger noise increases. Similar trends are seen for Fig. 4(b) and (c), where the descent angles are also steep. The noise character at these angles was not substantially impulsive, with or without pitch controls, indicating a less than dominant role for BVI noise in the trends observed.

Fig. 4(d)-(g) are for descent angles and speeds where the rotor generally operates in or about its own wake. BVI noise would be expected to be most intense for these cases and, indeed, the baseline cases have higher levels than those at steeper angles, especially at lower μ. Subjectively, the impulsive character of the noise was quite noticeable. The use of 4P collective control is seen to reduce the noise for a range of azimuth control angles for these lower μ values. The greater pitch amplitude of $\theta_C = -1.0°$ is seen to be most effective at the lowest μ values of 0.14 and 0.20, while the smaller $\theta_C = -0.5°$ is more effective at the somewhat higher $\mu = 0.266$

value. The net reductions were due to substantial impulsive BVI noise reductions along with some increase, particularly in the low frequencies, in the noise of other noise components. Note that the azimuthal range where reductions occur, roughly between $\Psi = 45°$ and $75°$, correspond to the expected BVI locations in reference 7. This is consistent with the concept that reductions in blade loading and vortex strength in the vicinity of BVI occurrences should reduce BVI noise.

Fig. 4 (h)-(j) are for mild descent angles where the wake generally lies below the rotor. At the lower μ value of Fig. 4(h), the 4P pitch is seen to reduce noise using both $\theta_C = -0.5°$ and $-1.0°$. For the higher advance ratio of Fig. 4(i), $\theta_C = -0.5°$ is more effective. No net benefit is seen for pitch control in Fig. 4(j) for $\mu = 0.30$.

A portion of the test was directed at more clearly defining flight regimes where higher harmonic pitch control can be used to reduce BVI noise. Fig. 5 shows, for the baseline (no control) case, a contour map of noise levels for a broad range of "full scale helicopter" descent angles Θ and advance ratios μ. A contouring program was used with measured levels at the test grid points indicated. Some test grid points are seen to be overlaid by letters which correspond to the parts of Fig. 4. For reference, the noise levels determined during this part of the test are shown in Fig. 4 by the solid symbols. These are seen to be matched within one dB to the corresponding open symbols which demonstrates the degree of repeatability. The BVI noise is seen to be most intense at lower speed and descent angles corresponding to normal landing approach for helicopters. The tunnel limitation, which prevented acquisition of data at advance ratios below $\mu = 0.11$, is unfortunate because of the importance of BVI noise at low μ. The intense BVI impulsive noise lies in a region which is approximately centered about $\Theta = 9°$ at $\mu = 0.11$ and ranging to $\Theta = 6°$ at almost $\mu = 0.3$. The flight conditions of Figs 4(d)-(f) are positioned in this region, whereas the other points are seen to border it. The level and climb flight regimes are dominated by non-impulsive loading and broadband noise.

The flight matrix of Fig. 5 was also conducted for a 4P pitch control of $\theta_C = -1°$ and $\Psi_C = 60°$. While this pitch is seen in Fig. 4 to not always be optimum, it appears to give representative noise reductions for flight conditions where reductions were found. Fig. 6 shows the contour plot for the resultant levels. The effect on the noise is dramatic since the particularly intense BVI noise region is eliminated. Fig. 7 shows the relative change between the levels of Fig. 6 and that of Fig. 5. Noise reduction (negative level change) is seen limited to the landing approach flight regime where BVI noise is most important. The maximum net reduction found was 4.7 dB, at $\Theta = 8.5°$ and $\mu = .11$. Noise tends to increase where BVI noise is not dominant for baseline conditions; that is, for climb, level flight, steep descent, and high speed flight for all angles. As mentioned, the particular 4P pitch control amplitude and phase used is not always optimum. Based on the discussion of Fig. 4, the noise reduction region could be expanded for 4P control over that shown by employing less amplitude in the other fringes of the region.

The practicality of implementing specific higher harmonic pitch control for noise reduction will depend in part on accompanying vibratory loads. Early analysis reveals that the vibratory forces and moments, as measured by the six-component balance mounted below the model base, consistently experienced increases (primarily in the 4P components) with the application of the pitch control over that measured at baseline conditions. Of particular concern is that the baseline and pitch control loads were phased such that the resultant 4P loads tended to be maximized at minimum noise (azimuth control angle $\Psi_C \approx 60°$ to $75°$) and minimized at maximum noise ($\Psi_C \approx 15°$ to $30°$). This trend was noted throughout the test matrix.

CONCLUDING REMARKS

The reduction of impulsive BVI noise by higher harmonic pitch control appears to be a viable concept. For landing approach conditions, where noise reductions occur, the impulsiveness of the noise was found to be diminished and replaced in

part, by noise of a more low frequency character. The impulsive noise reductions appear to correspond to reductions in blade pitch and vortex strength in the vicinity of BVI occurrences. All 4P pitch control cases tested showed increased vibration levels. The vibration concern, as well as a more detailed quantification of the noise results, must be addressed in subsequent analyses. Important questions of noise directivity effects are not readily addressable with the present data base. In the present study, aeroacoustic testing in heavy gas was demonstrated for the first time.

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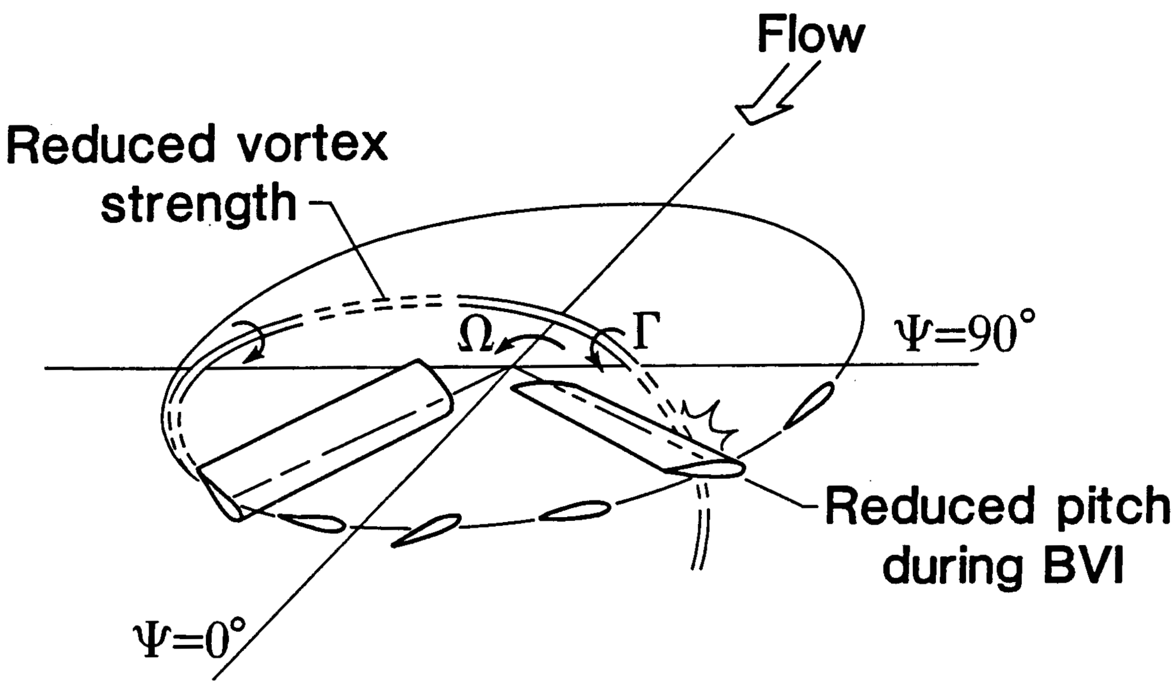

Fig. 1. Illustration of noise reduction concept

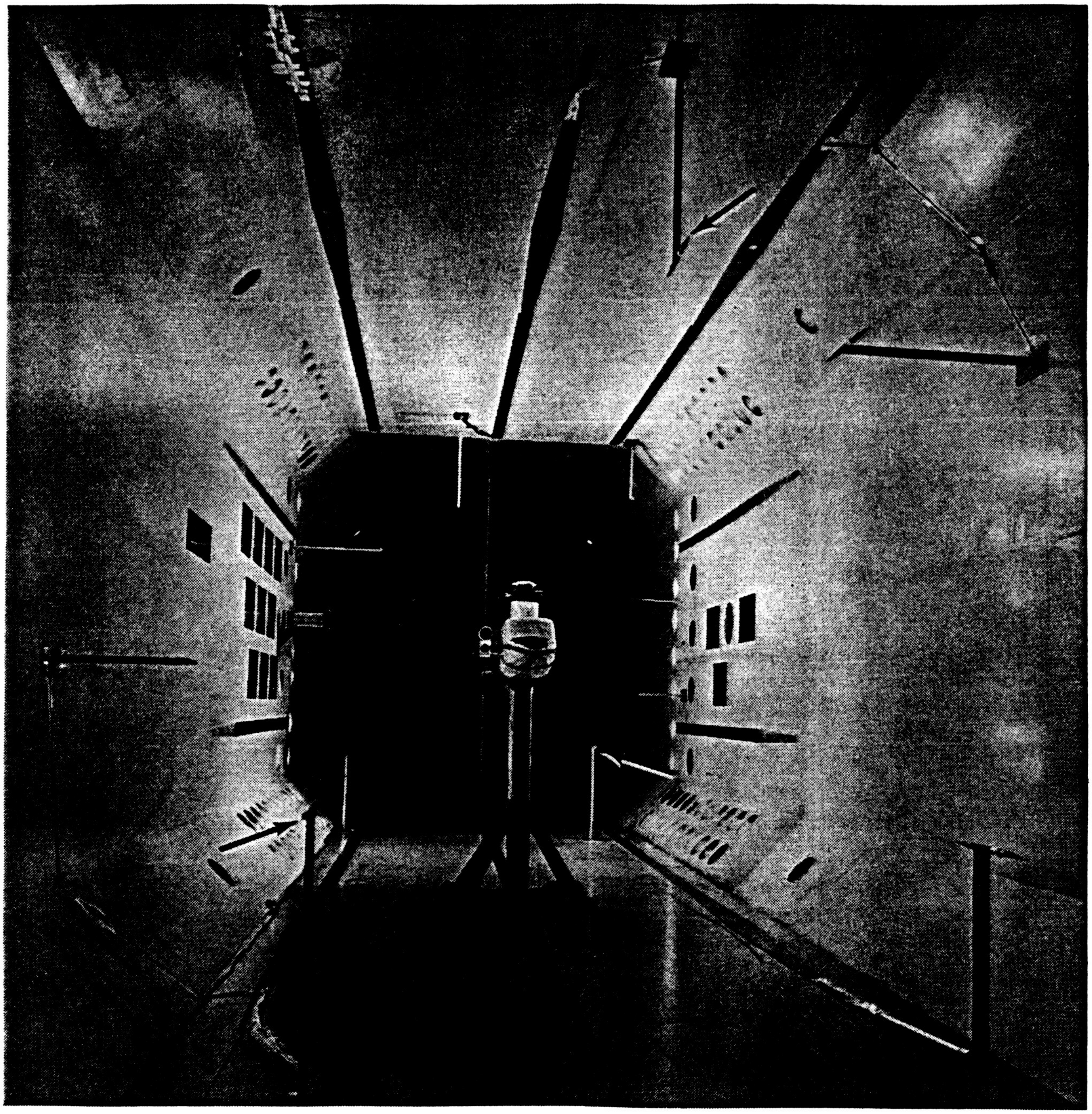

Fig. 2. Noise test set-up with ARES model in the TDT. Arrows show microphones of interest.

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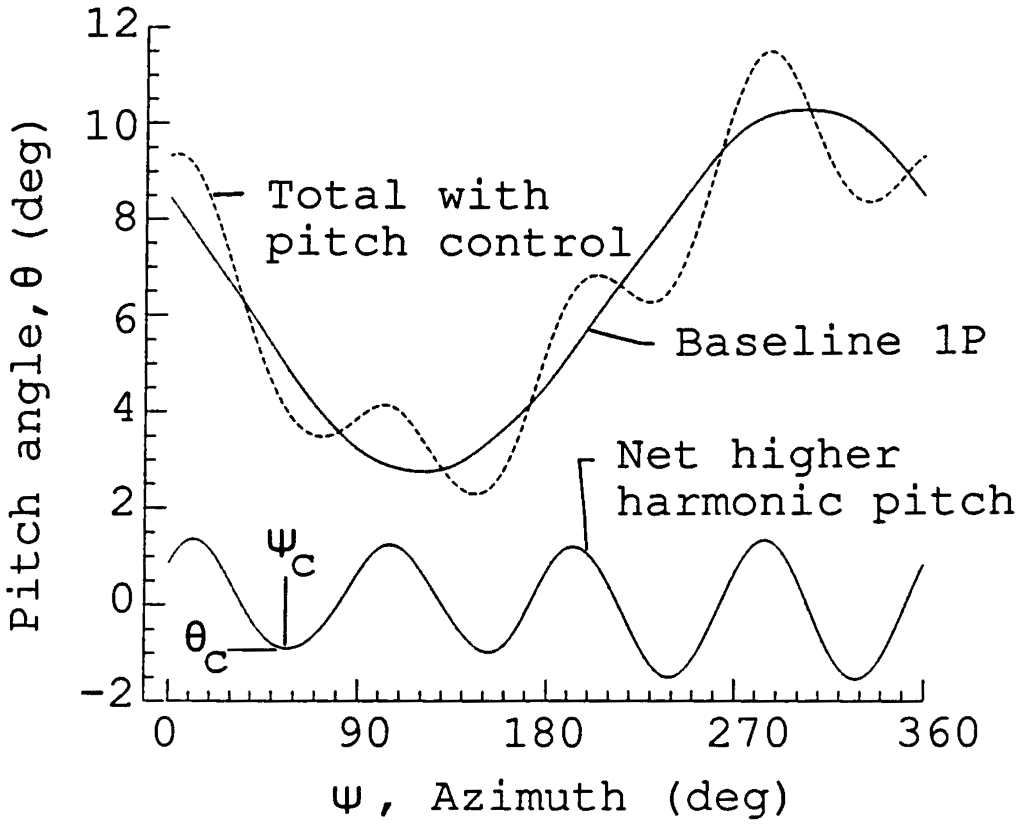

Fig. 3. Blade pitch angle θ versus azimuth Ψ for $\mu = 0.266$ and $\alpha = 0°$. Pitch control is 4P collective with $\theta_c = -1.0°$ at $\Psi_c = 60°$.

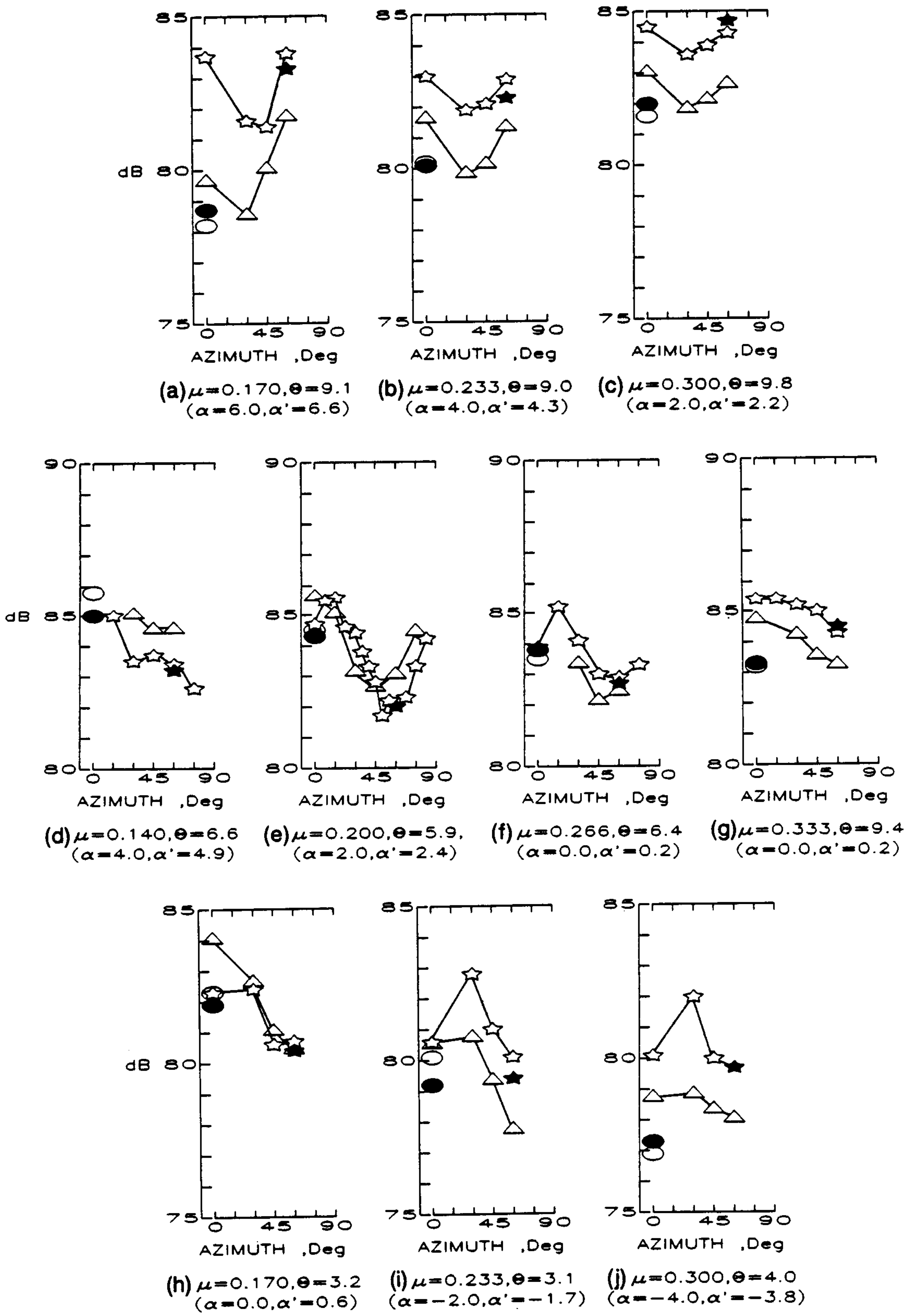

Fig. 4. Noise level (dB) variations with different 4P pitch control amplitudes θ_c and azimuth Ψ_c. Symbols are for θ_c=0° (baseline), O; for θ_c=-0.5°, Δ; and for θ_c=-1.0°, ☆ . Solid symbols are repeat cases.

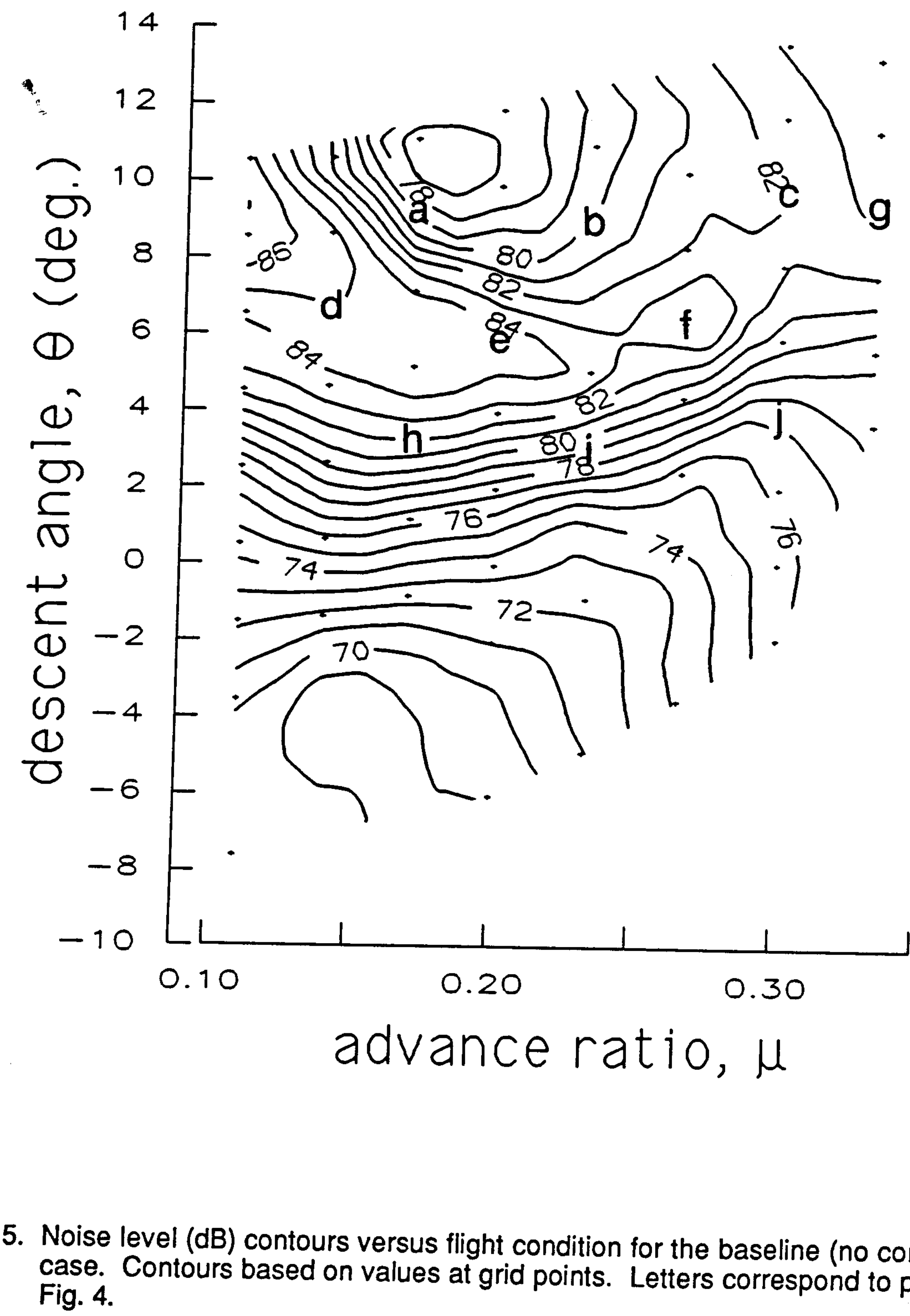

Fig. 5. Noise level (dB) contours versus flight condition for the baseline (no control) case. Contours based on values at grid points. Letters correspond to parts of Fig. 4.

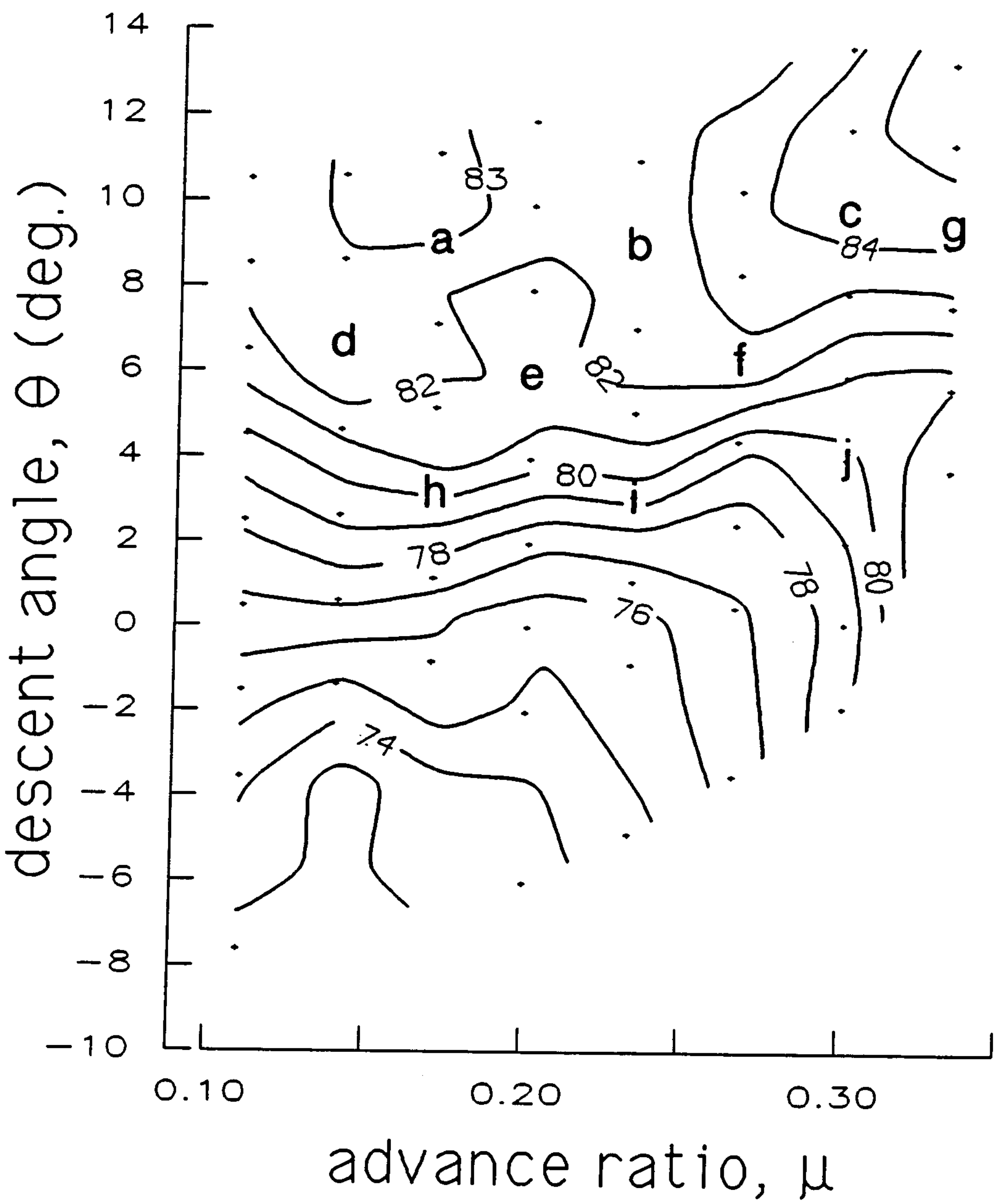

Fig. 6. Noise level (dB) contours versus flight condition for the 4P pitch control $\theta_c = -1.0°$ and $\Psi_c = 60°$ case. Letters correspond to parts of figure 4.

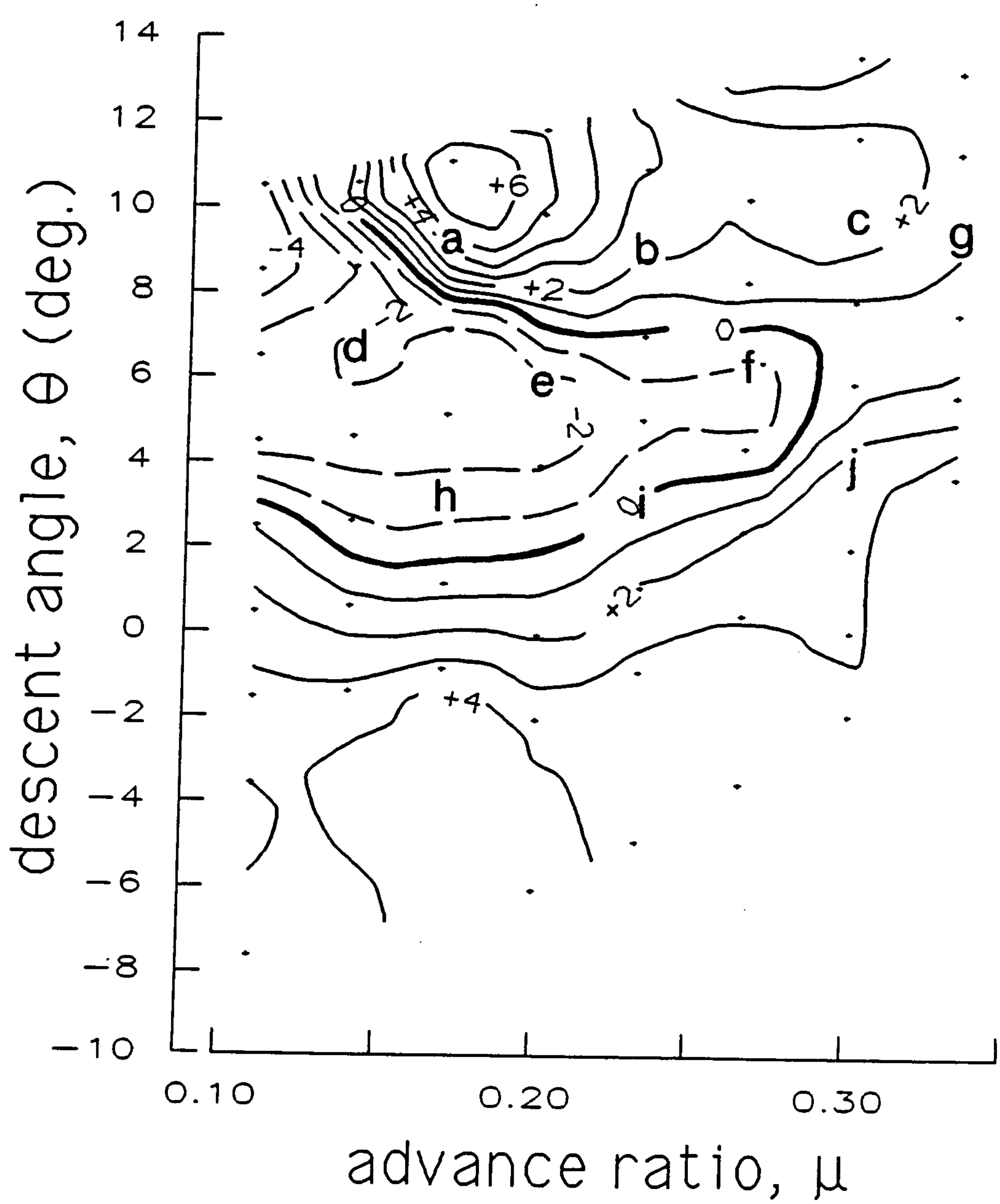

Fig. 7. Noise level (dB) differences between the pitch control case of Fig. 6 and the baseline case of Fig. 5. Negative values show noise reductions for control case. Letters correspond to parts of figure 4.

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National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-101624 AVSCOM TM-89-B-005	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Reduction of Blade-Vortex Interaction Noise Using Higher Harmonic Pitch Control		5. Report Date July 1989
		6. Performing Organization Code
7. Author(s) Thomas F. Brooks, Earl R. Booth, Jr., J. Ralph Jolly, Jr., William T. Yeager, Jr. and Matthew L. Wilbur		8. Performing Organization Report No.
		10. Work Unit No. 505-63-51-06
9. Performing Organization Name and Address NASA Langley Research Center and Aerostructures Directorate USAARTA-AVSCOM Hampton, VA 23665-5225		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001 and U.S. Army Aviation Systems Command St. Louis, MO 63120-1798		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

An acoustics test using an aeroelastically scaled rotor was conducted to examine the effectiveness of higher harmonic blade pitch control for the reduction of impulsive blade-vortex interaction (BVI) noise. A four-bladed, 110 in. diameter, articulated rotor model was tested in a heavy gas (Freon-12) medium in Langley's Transonic Dynamics Tunnel. Noise and vibration measurements were made for a range of matched flight conditions, where prescribed (open-loop) higher harmonic pitch was superimposed on the normal (baseline) collective and cyclic trim pitch. For the inflow-microphone noise measurements, advantage was taken of the reverberance in the hard walled tunnel by using a sound power determination approach. In the paper, initial findings from on-line data processing for three of the test microphones are reported for a 4/rev (4P) collective pitch control for a range of input amplitudes and phases. By comparing these results to corresponding baseline (no control) conditions, significant noise reductions (4-5 dB) were found for low-speed descent conditions, where helicopter BVI noise is most intense. For other rotor flight conditions, the overall noise was found to increase. All cases show increased vibration levels.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Helicopter rotor acoustics Blade-vortex interaction noise Higher harmonic control	Unclassified-Unlimited Subject Category 71

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	18	A03

NASA FORM 1626 OCT 86